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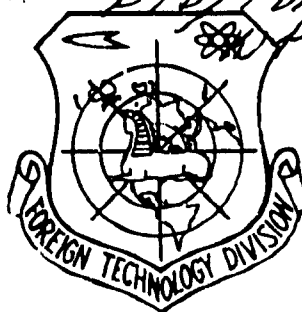
SUPERSONIC COMBUSTION AND ITS APPLICATION
IN HYPERSONIC JET ENGINES

by

P. Wolanski

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By: P. Wolanski

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ABSTRACT: Processes taking place during supersonic combustion of an air-hydrogen gas mixture are discussed on a theoretical basis. Attempts to analyze these phenomena are supported by results on the research. Two fundamental types of supersonic combustion are distinguished; combustion controlled by the (mixture formation processes), and shock induced. In the first type of combustion, the gaseous fuel is injected trangentially into the air jet at a rate and pressure similar to those of the air. If the temperature and pressure of the mixture are sufficiently high, spontaneous combustion occurs and the burning velocity is a function of the diffusion rate of the fuel and air jets. If the air temperature and pressure and low, supersonic combustion must be initiated by some type of ignition e.g., with a preheated fuel jet. This process is considered to be heat convection controlled supersonic combustion. Both of these processes are studied and described in detail. Shock inducted combustion, which takes place when air and gaseous fuel are mixed in the supersonic jet and are ignited by the shock wave causing a rise in pressure and temperature is treated in more general terms. Orig. art. has: 3 formulas and 17 figures. English translation: 17 pages.

SUPERSONIC COMBUSTION AND ITS APPLICATION IN HYPERSONIC JET ENGINES

Piotr Wolanski

Part I

The first theoretical part of this article contains discussed problems of supersonic combustion with a special consideration of supersonic combustion controlled by diffusion and by thermal convection and a superficial representation of the problem of detonation combustion. The theoretical part of the article is based on investigation results and analytical effort of comprehending this problem.

c_p - proper heat at constant pressure,

Ma   - Mach number,

p[ata]   - pressure,

Q [kacl/kG] - thermal energy separating per unit of stream mass,

$\bar{Q} = Q/c_p T$ - Damkohler's second number,

T [$^\circ$K]   - temperature,

u [m/sec] - velocity,

ρ - density,

τ - time.

Combustion in a conduit of constant cross section in a subsonic stream leads on one side to a drop in static pressure and total pressure as well as in density behind the flame front, and on the other hand, to a rise in Mach number in this stream. When combustion takes place in a supersonic jet, total and static pressure rises, but the Mach

number and density decrease. The preservation of the Mach number leads to a conclusion, that Mach number 1 (Ma = 1) constitutes a limitation in the delivery of heat in a subsonic, as well as supersonic jet. When the Mach number upon heat delivery will reach the value 1, it is stated that the jet is thermally saturated. The amount of heat, which can be delivered to the flowing through gas stream (jet), depends upon the initial Mach number (Fig. 1).
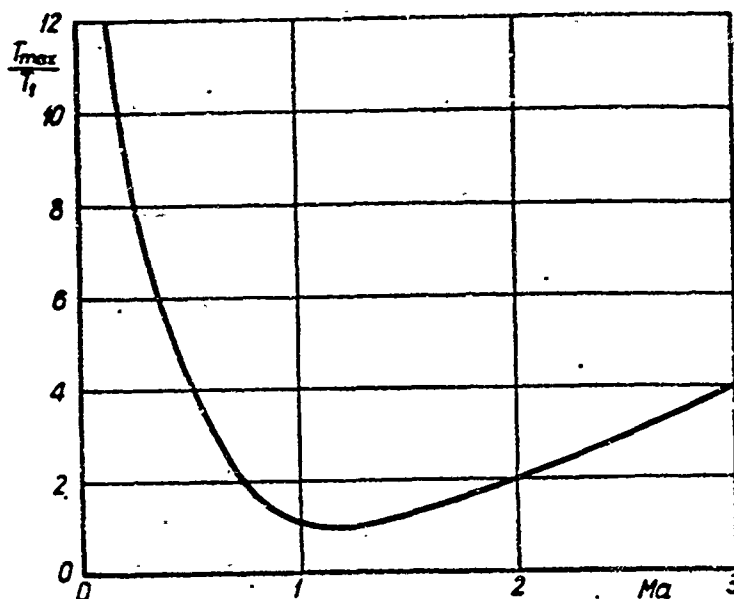

Fig. 1. Change in heat saturating the stream (jet) in dependence upon initial Mach number.

Thermal saturation leads to the existence of maximum temperature, to which could be delivered gas flowing through a cylindrical conduit (Fig. 2).

The described behavior of the gas jet (stream) at the delivery of heat (combustion) is plainly evident on the outline of stream (jet) density, changes in the function of Mach number for various values of other Damkohler numbers $\overline{Q}$ (Fig. 3)

From the represented outline, there can be distinguished two basic types of supersonic combustion: the first one -- when combustion takes place without the existence of a densification jump, called combustion controlled by mixture creation processes, and the second - when combustion takes place at the existence of a densification jump called detonation combustion or combustion on a shock wave.

In case of supersonic combustion occurring without the existence of a shock wave, the fuel in the gaseous state is injected tangent to the flowing through air stream with velocity and pressure close to velocity and pressure of the air stream. If the pressure and temperature of the mixture are sufficiently high, then a spontaneous combustion process begins. The rate of the combustion processes will depend upon the rate fuel stream and air stream diffusion. That diffusion will be greater, the greater the density difference of both streams and the greater the turbulence will be. This type of

combustion in a supersonic stream (jet) is called supersonic combustion controlled through diffusion.
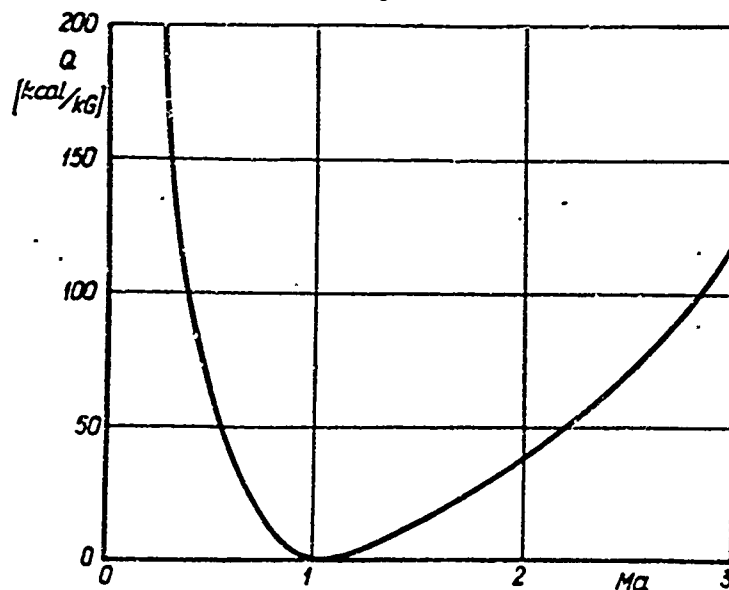

Fig. 2. Change in maximum stream (jet) temperature in dependence upon initial Mach number. T_1 - initial temperature.
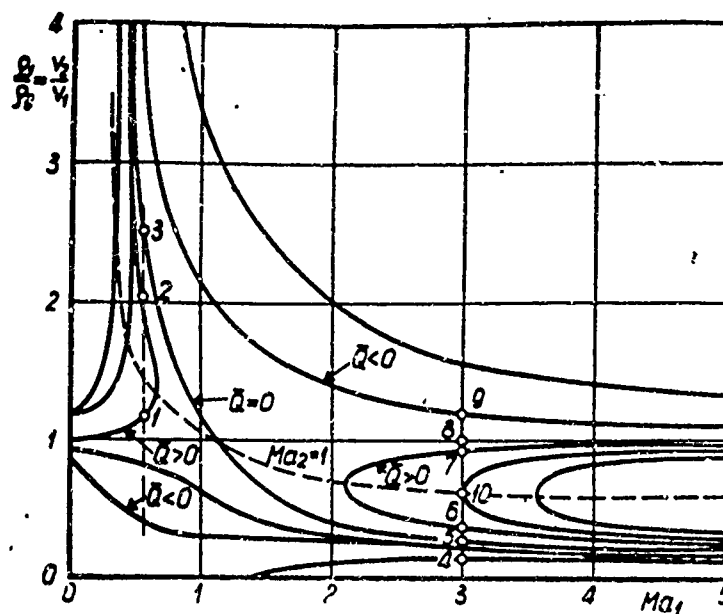

Fig. 3. Established single parameter flow through with heat delivery.

1 - simple subsonic combustion,
2 - rarefaction jump and conbustion,
3 - rarefaction jump.
4 - condensation jump plus heat tapping,
5 - condensation jump
6 - condensation jump plus combustion

7 - combustion without jump,
8 - no processes take place
9 - heat tapping without jump,
10 - Chapman-Jouguet point.

If the pressure and temperature of the air stream are low, super-sonic combustion may take place, but a certain type of pilot flame must be applied. It could be a heated-up stream of fuel or a stream of fuel combusted in advance for the purpose of raising its temperature. This type of combustion is called supersonic controlled by thermal convection. It is possible to realize at a smaller Mach number than the previous type.

Detonation combustion takes place in the case when the air and combustive gas are mixed in a supersonic stream and when the stream passes through a shock eave temperature and pressure in the stream rise so considerably, that combustion does take place. At such an arrangement, the gaseous fuel and and air must be mixed at such a low pressure and temperature, as to exclude the possibility of spontaneous combustion of the mixture in front of the shock wave. In the wave starts the ignition of the mixture, and combustion takes place very rapidly, so that the pressure and temperature jump in the wave takes place by an order of magnitude. In that system, the shock wave (detonation wave) is described by combustion processes and is higly sensitive to their changes.

Combustion processes

As is known, the combustion time of a mixture can be divided into two periods: the first, in which a part of the processes not separating considerable amounts of heat and characterized by a slight change in temperature, called delay in ignition, takes place and the second part, in which the proper combustion phase appears, a part characterized by considerable heat separation and large rise in temperature, called the reaction time.
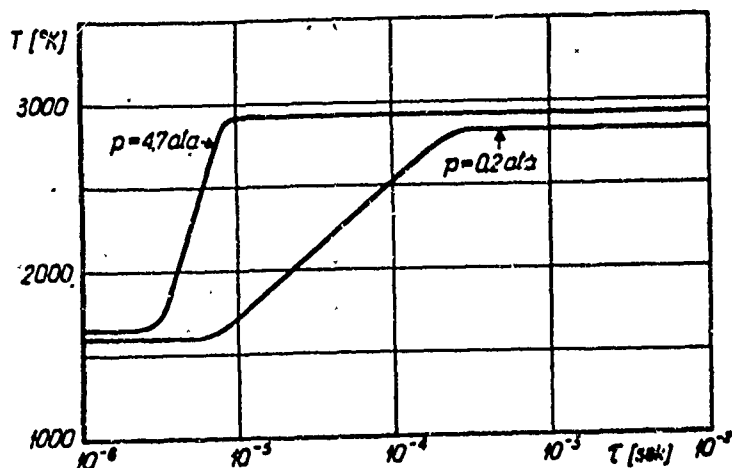

Fig. 4. Effect of static temperature of the stream and pressure on the combustion time of hydrogen and air mixture.

During the first phase, the heat emitted during the creation of water is equilibrated by the process of oxygen and hydrogen molecule

dissociation. The decline of monoatomic oxygen and hydrogen in the following combustion phase causes a rapid temperature rise.
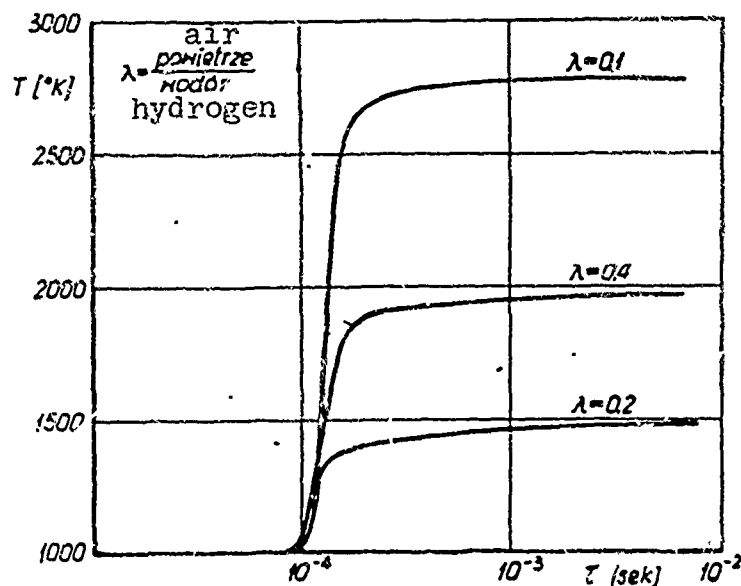

Fig. 5. Effect of mixdure composition on combustion time.

A delay in ignition depends upon pressure and temperature of the forming mixture (Fig. 4) and does not depend upon the change in mixture composition (Fig. 5).

From the experiments and analyses carried out [1, 2], derived were the functional dependerces on the ignition lagging time and reaction time as pressure and temperature functions. The ignition delay time should be proportional to the pressure at a constant temperature. The equation for the ignition delay time was formulated for the sphere of mixdure component λ 0.4 to 2.0 and is represented in the following form:

$$p\tau_z = 8 \cdot 10^{-3} \cdot e^{9600/T} \quad [\mu sek]$$

The equation for the reaction time was formulated for the sphere of pressures between 0.2 ÷ 5.0 absolute atmosphere and static temperatures of stoichiometric mixture in a sphere of from 1000 ÷ 2000°K and has the form:

$$p^{1.7}\tau_r = e^{-1.12\,T\,1000} \quad [\mu sek]$$

The combustion time is the sum of the ignition delay time and of the reaction time and is presented as follows:

$$\tau_s = \tau_z + \tau_r = \frac{8 \cdot 10^{-3}}{p} e^{\frac{9600}{T}} + \frac{1}{p^{1.7}} e^{-\frac{1.12\,T}{1000}} \quad [\mu sek].$$

From the equation it is evident, that the ignition delay time and reaction time, and namely also the resultant combustion time, decrease with a rise in static pressure and static temperature of the mixture. Knowing the influx direction of changes in parameters of the combustion gas, it is well possible to regulate the combustion time, and namely the length of the flame. The length of the flame

depends also upon the velocity ratio of the mixing streams. That dependence is presented in Fig. 6. Fig. 6a shows the arrangement of hydrogen stream injection into the air stream with a description of parameters with application of the reference system. Fig. 6b represents the position of the flame at various stream velocity ratios u_p/u_{II}.
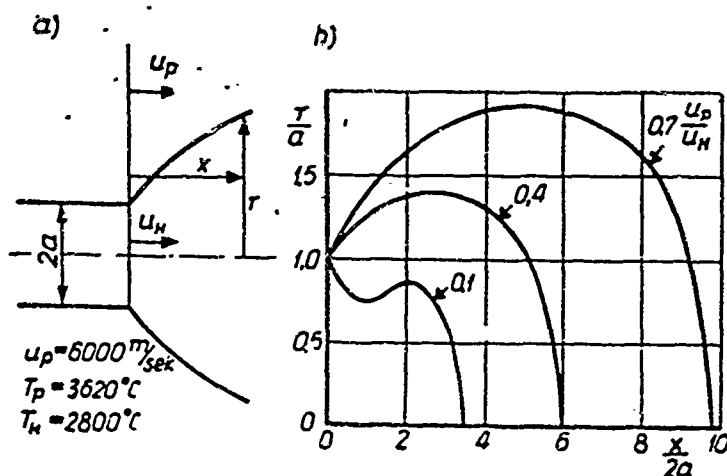

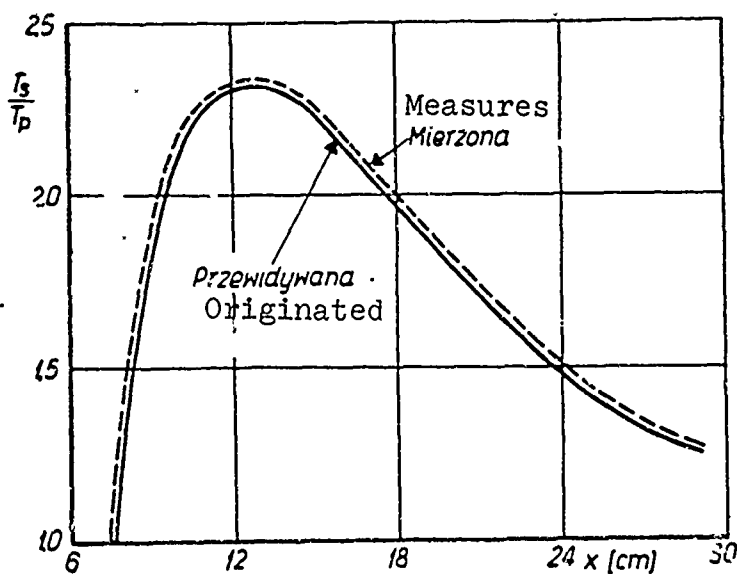Fig. 6. Arrangement of flame surface

Fig. 7. Temperature distribution along flame.

From the represented phase, it is clearly evident that the length of the flame does not depend only upon the velocity ratio u_p/u_H, but also upon the value of parameter a. And so, for the parameters of gases given in Fig. 14a and value a of the order of 25 mm of flame length is of the order of 300 mm.

Applying the proper analysis of the entire complex of problems connected with supersonic combustion, it is possible quite accurately to foresee the picture of the phenomena taking place in these processes. A comparison of flame temperatures theoretically calculated with temperatures measured in time of experimentation, is shown by Fig. 7. The differences are minimum.

Supersonic combustion without shock wave

Supersonic combustion controlled by diffusion

To illustrate the nature of supersonic combustion controlled by diffusions, we will examine two symmetrical gas streams of various compositions, velocity and temperature in the chamber at great flow through velocity [1]. Mixing can be laminary or turbulent in dependence upon the concentration of the stream. In dependence upon the nature of flow through and upon stream parameters, the mixing process may take place without the need of existence of a large pressure differential. For example, lets take two gases of the same pressure applied concentrically. The central gas is hydrogen, the outer, air. This is illustrated by the phases presented in drawings 8, 9, 10. The aid moves at a velocity $u_p = 921$ m/sec, it has a temperature $T_p = 3393°K$ and pressure $p_p \approx 0.38$ ata; hydrogen has a velocity $u_H^p = 0.38$ ata; hydrogen has a velocity $u_H = 310$ m/sec, temperature $T_H = 898°K$ and the pressure $p_H = 0.38$ ata. When the intermixing streams do not chemically react with each other, the process of their mixing takes place according to dynamic rules of fluids (Fig. 8a). Hydrogen diffuses gradually in the direction of the air stream, and the concentration of air in the hydrogen stream rises gradually (Fig. 8b). The distance, on which stream concentrations are equalized, does not ddpend upon the initial diameter of the hydrogen stream.

Let us now examine the mixing process of the streams at a simultaneously occurring chemical reaction. In case of the existence of large static pressures and temperatures, the reaction time is so short (much shorter than the flow through time) that it is not being considered in the analysis of the process, and the chemical processes are dependent upon local concentrations of reacting atoms and local pressure and temperature values. In this case combustion is controlled exclusively by the diffusion processes creating the mixture. The distribution of hydrogen concentration along the mixing streams is shown in Fig. 9a, and the concentration of components in the axis of the stream is shown in Fig. 9b.

For low pressures and gas temperatures, the streams react freely and the mixture forms more rapidly than the chemical reaction will occur (combustion). The periods of chemical reactions are of the order of flow through times, and the phenomena of mixing and combustion are more independent. In this case, mixing is rapid and the heat created during combustion increases only locally the reaction rate. The occurrence of the process is shown in Fig. 10.
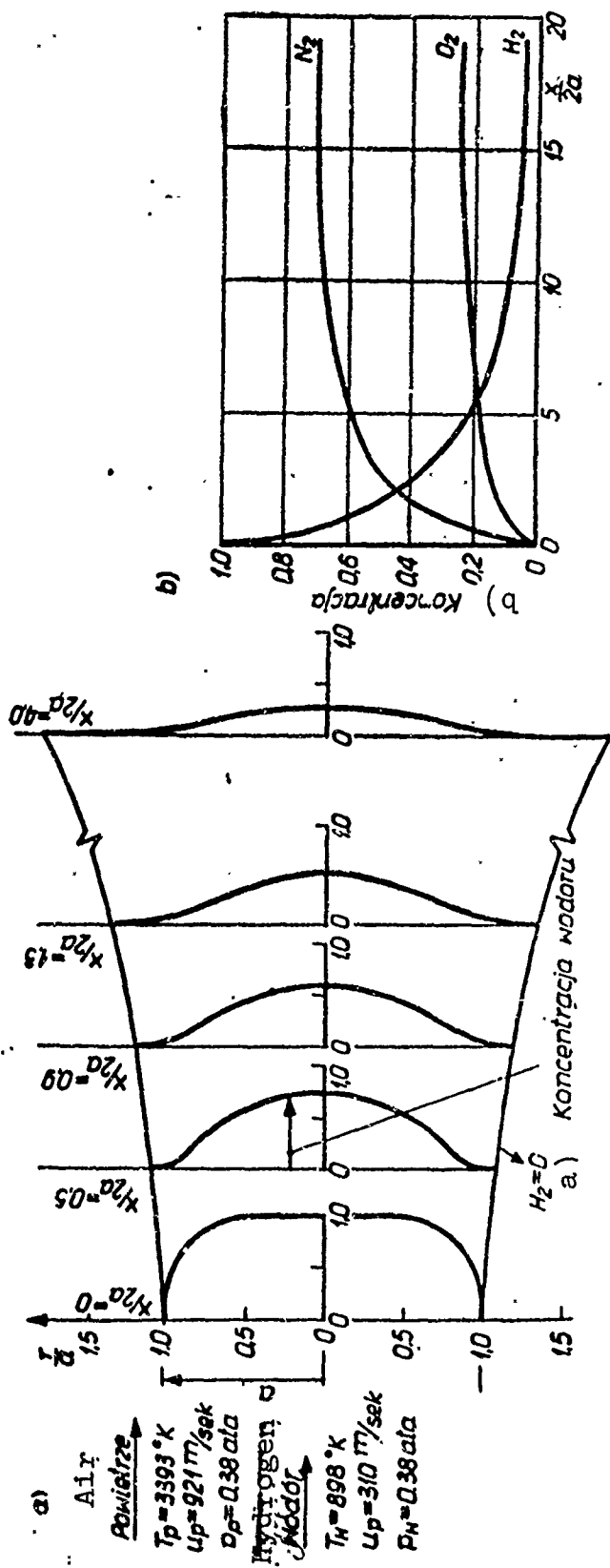
Fig. 8. Mixing of supersonic air and hydrogen ssreams without chemical reaction (combustion).
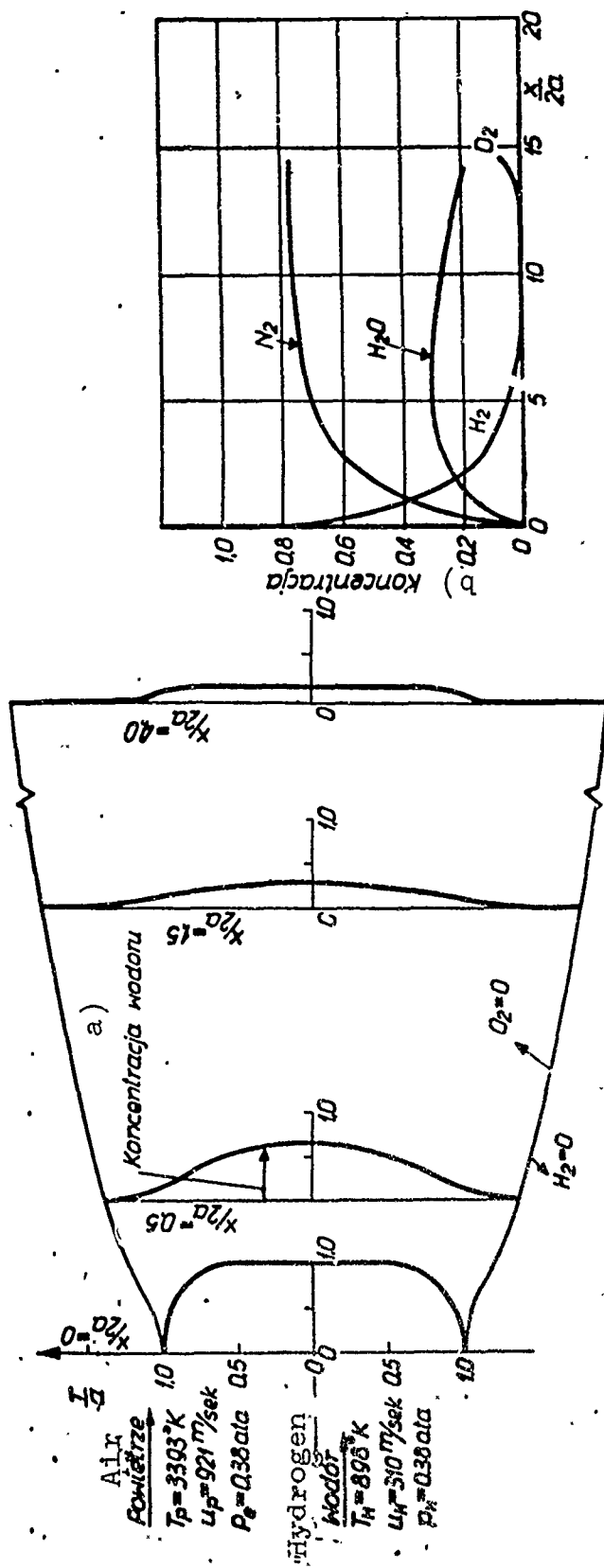KEY: a) concentration of hydrogen; b) concentration.

8

Fig. 9. Mixing of supersonic air and hydrogen streams at simultaneous occurring chemical reactions.

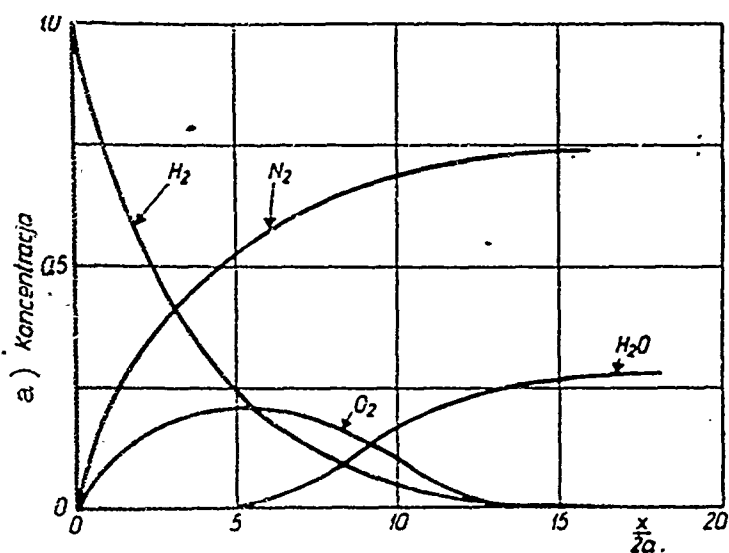KEY: a) hydrogen concentration; b) concentration.

Fig. 10. Concentration in the axis of the stream at a definite level of chemical reaction.
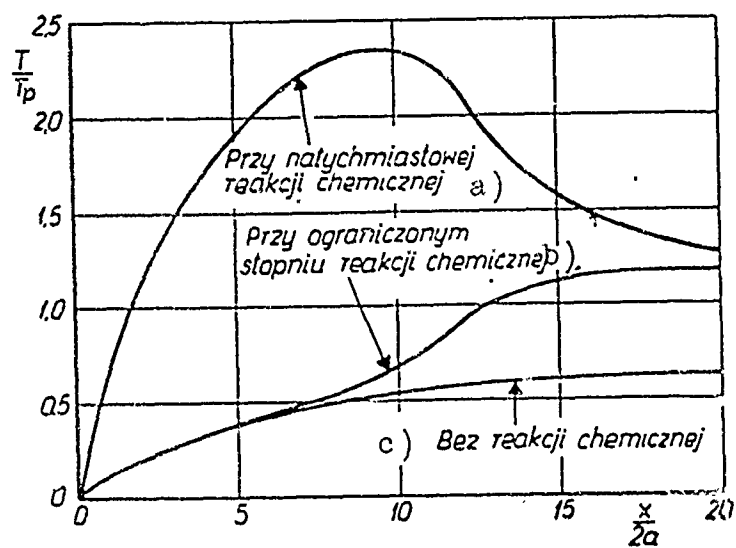KEY: a) concentration.

Fig. 11. Change in static temperature along the axis of the stream.
KEY: a) at immediate chemical reaction; b) at limited degree of chemical reaction; c) without chemical reaction.

Fig. 11 shows the change in static temperature along the axis of the stream for three described instances: the first one when there is no chemical reaction, second - when the reaction is like a flash and third, when the reaction takes place only after the stream has mixed. Figs 12a and 12b show temperature distribution in the flow through for the second and third cases.

The combustion process controlled by diffusion of two super-sonic streams is constant and changes in dependence upon local temperature, pressure and density changes. Pressure changes caused by irregular combustion, shift only in the direction of the flow through and cause no physical or chemical disturbances in the place, where they were caused. There are therefore no premises for the origination of deficiency in the stream.

During the stream mixing process, the encountering particles from air-oxygen and hydrogen react among themselves yielding water. The flame originates at that reaction, and the separated heat is transmitted to the mixing area of the stream. On the outside of the stream mixing area, the flow through is rich in oxygen and contains: oxygen water vapor and nitrogen. Within the mixing area, the flow through is rich in hydrogen and contains: hydrogen, water vapor and nitrogen. These two areas are divided by a surface, on which stoichiometric conditions exist and where combustion takes place. These phenomena are represented in Fig. 13. Area A is the area of 100% hydrogen content, area B of 100% air content, in area C - if there is no combustion - the gas forms a nitrogen, oxygen and hydrogen mixture. If combustion can take place in the same degree as the stream mixing process, local concentrations in area C depends upon the chemical processes taking place there. In case of the existence of a very rapid chemical reaction, area A can be divided into two areas: area C_2 in which the stream is rich in oxygen and contains additionally nitrogen and water vapor and area C_1, which is rich in hydrogen and also contains nitrogen and water vapor. Beyond the C - X line, the gas is stoichiometric, deprived of free hydrogen and oxygen, and contains only water vapor and nitrogen. The surface along line X - X is called the flame layer.

Experiments indicate, that the concentration of hydrogen along the stream changes proportionally to $\left(\sqrt{\varrho_H u_H / \varrho_p u_p} / x\right)^2$.

Supersonic combustion controlled by thermal convection

The thermal convection process can be utilized in combination with the diffusion process to control the mechanism of supersonic combustion. To illustrate this concept, we will examine a small gas stream having a high static temperature, surrounded by a flow having low static temperature (Fig. 14). Both streams have the same pressures. Since mixing takes place, the concentration of gases in both streams changes gradually, namely also the static temperature of the stream changes. The outer gas is heated during the mixing with hot central gas. If the forming mixture does not chemically react, the temperature in the axis of its stream decreases gradually. But if the central gas is prematurely combusted and its temperature is sufficiently high, the outer gas will react and combustion will take place. The heat
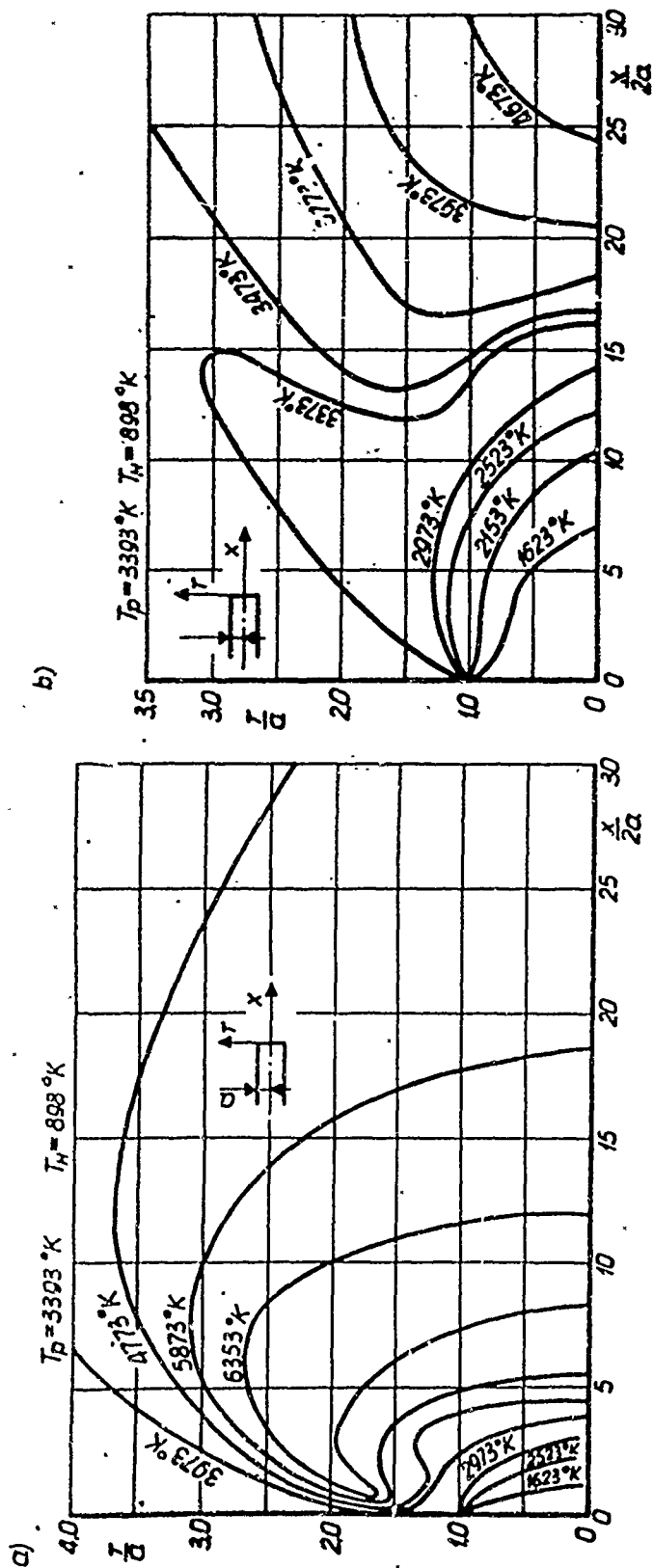
Fig. 12. Distribution of temperatures in flow:
a) chemical reactions occur simultaneously with stream mixing process;
b) chemical reactions take place after the streams are mixed.

The heat generated and transmitted through the reacting gases maintains the temperature in the central flow area and if the thermal balance is positive, combustion takes place during the mixing of streams and advances in the direction of the outer flow. Propagation of the flame is controlled by the mixing process of the streams. An example presented in Fig. 14, pertains to combustion products mixed with hydrogen, which are brought to the air-propane stream of stoichiometric composition and low static temperature.
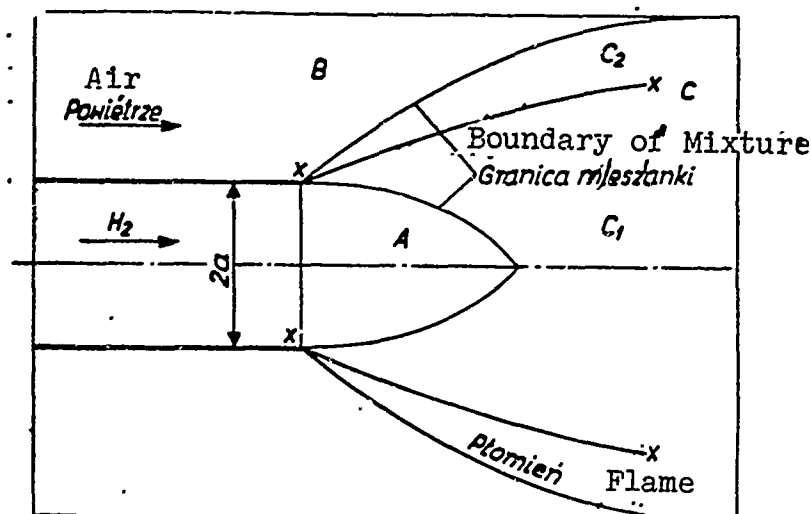

Fig. 13. Model of mixture formation and of the reactions taking place between hydrogen and air streams.

Temperature distribution originated from combustion is shown in Fig. 14b. In this case, the central stream is similar to the igniter of the outer stream. Combustion takes place, because the central gas has such a high temperature, that the combustion processes begin before the outer stream will succeed in cooling the gas mixture.

Supersonic combustion controlled by diffusion would be impossible for an air-propane mixture, since it has a slow combustion rate. But since the combustion rate depends upon temperature, the processes are therefore subject to acceleration - but only local - where the temperature is sufficiently increased by the hot gas from the pilot flame. The intensity of the process will depend upon the balance between the heat created by combustion and the heat absorbed by the low temperature mix ure stream. The combustion mechanism described above, is of great practical importance, since it enables application of supersonic combustion already in the velocity area of Ma = 6-7.

Detonation combustion

At a thorough discussion of detonation combustion processes, they can be divided ubti twi griyps: 1) group, in which the detonation combustion processes take place on a simple wave, and 2) group, in which these processes take place on a slanting wave.

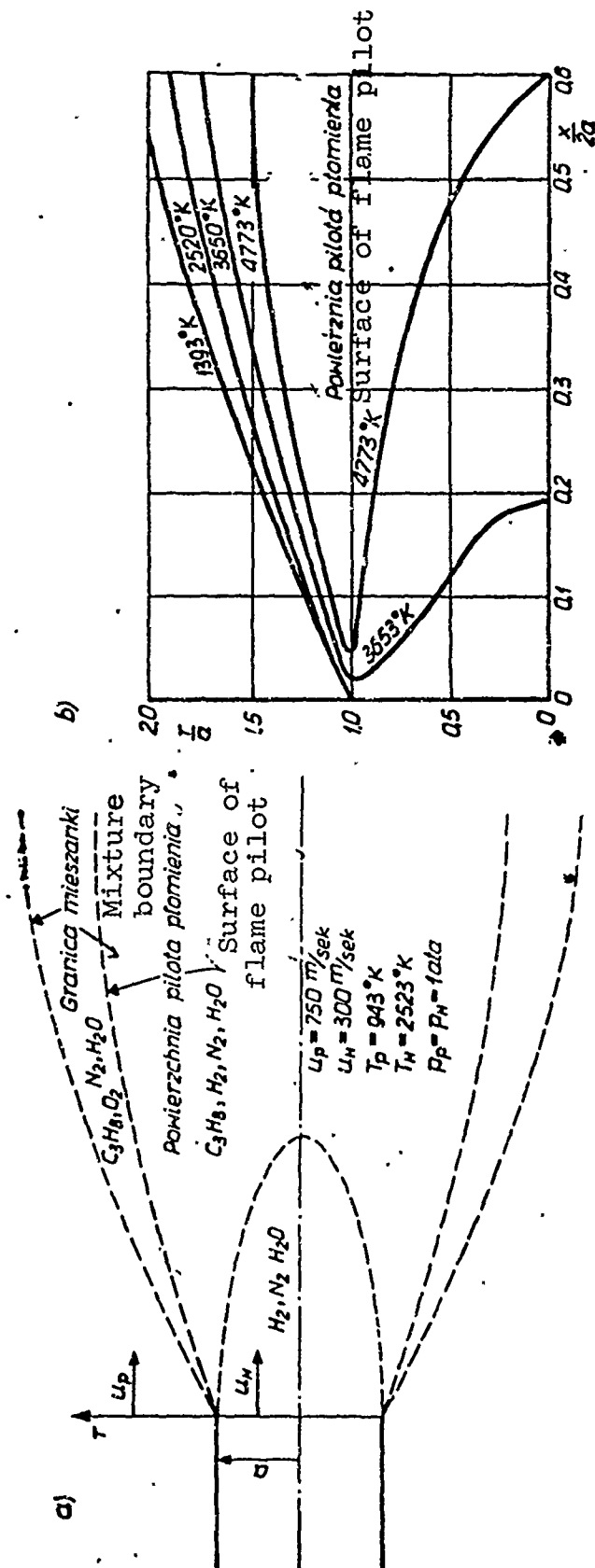Examination of changes in thermodynamic parameters of gas during

Fig. 14. Supersonic combustion controlled by thermal convection:
KEY: a) coabustion air-propane mixture with hydrogen-air flame pilot;
b) isotherms for this process.

the process of detonation on a simple wave is well evident on the out-
line of mono-parametric flow wi h the feeding of heat (Fig. 3). For
the case of flat at a Mach number equals 3 (point 5), two cases of de-
tonation combustion are theoretically possible - on a strong (point 6)
and on a weak shock wave (point 7). Points 6 and 7 are the states of
gas for two different feeding instances of the very same amount of
heat to a stream of the very same initial parameters. During com-
bustion on a strong wave (sharp detonation), the gas parameters behind
the wave are always subcritical ($Ma_2 < 1$), at a weak detonation the
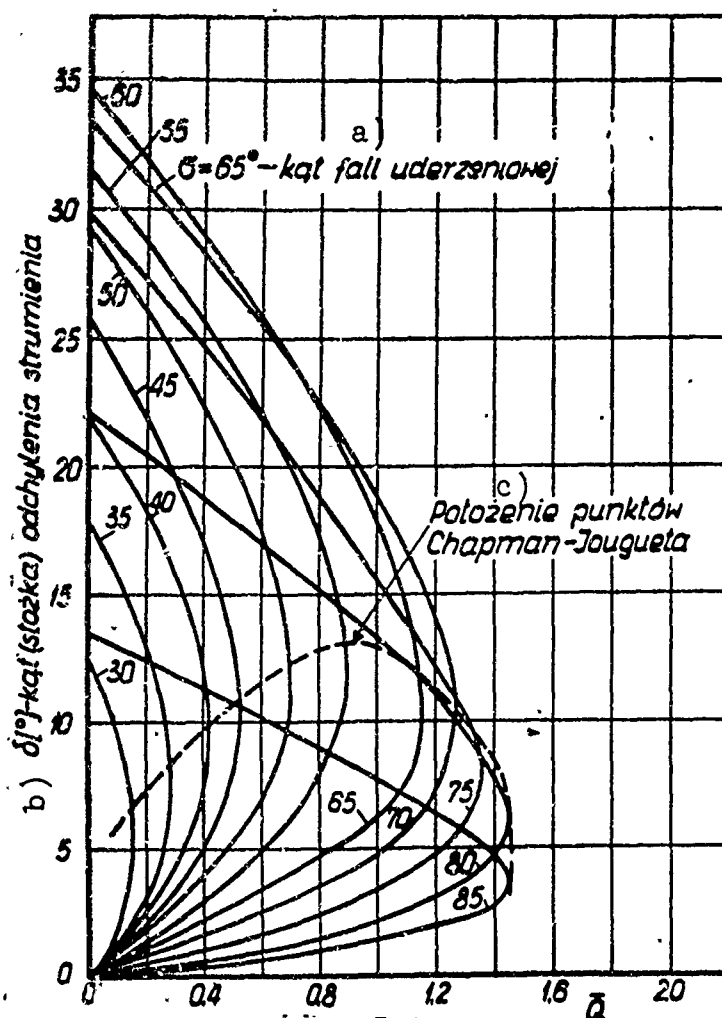
the flow is constantly supercritical ($Ma_2 > 1$).

Fig. 15. Theoretical properties of a slanting detonation wave
(initial Mach number of stream is 3).
KEY: a) angle of shock wave; b) angle (of column) of stream
deviation; c) position of Chapman-Jaguet points.

Increasing gradually, the amount of heat fed to the stream
reaches from both sides up to one point (point 10), in which a maximum
amount of heat is supplied into the stream, and the flow behind the
wave is critical. This point is called the Chapman-Jaguet point.

In supersonic tunnels, combustion on a strong shock wave was
repeatedly obtained. Static combustion was obtained for a whole area

(from point 5 to point 10), and the test results were repeated. Detonation combustions on a weak shock wave although theoretically possible, could not be obtained, since it is probably unstable.

In Fig. 15 are shown theoretical dependences between the angle of a cone and the other Damkohler number for a slanting detonation wave. The hatched line divides the area of a detonation wave from the area of a weak detonation wave. In a di-parametric flow there takes place a full analogy to the monoparametric flow and point, in conditions of which the componential normal velocity of gas behind the detonation wave is critical, it bears the same name. There can also exist such flow conditions, in which no constant flow conditions can be maintained. For example, for Q equalling 1.5 will not be obtained a constant flow at Ma = 3.

Studies of supersonic combustion were carried out in wind tunnels for hydrogen-air and methane-air mixtures, at velocities of about Ma = 3. The fuel was injected before the critical point, which assured creating of a uniform mixture in supersonic stream. Static pressure and static temperature were so selected, that the ignition of the mixture should not occur in free stream, but only on the shock wave.
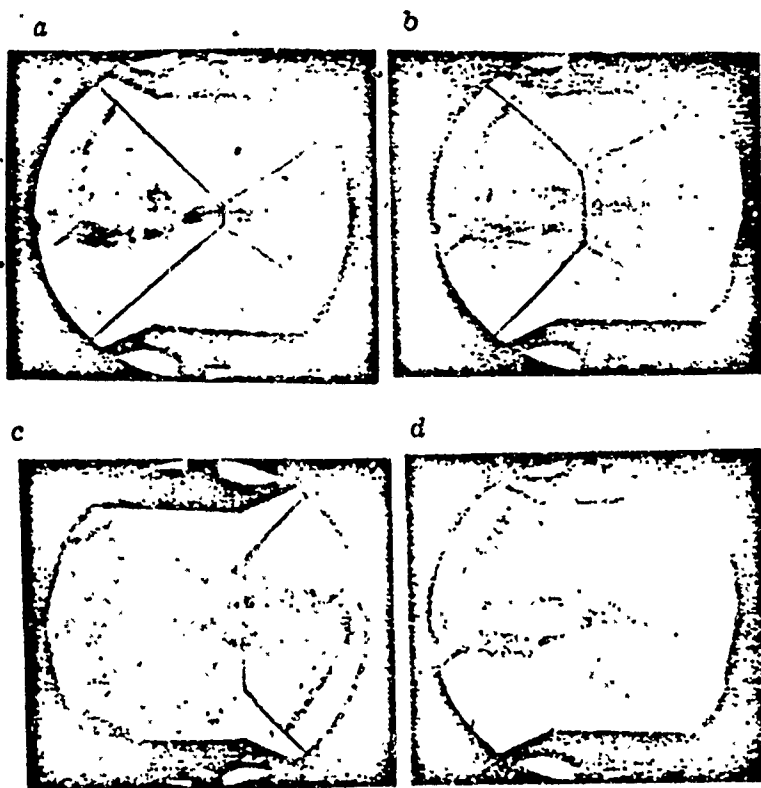

Fig. 16. System of waves for hydrogen-air mixture at a Mach number equal to 3.15 and at various Damkohler numbers (examined system of straight wave is in the center area of the measuring system.
a) without heat delivery, Q = 0;
b) with heat delivery at Q = 2,75:
c) rising detonation wave at Q = 3.75;
d) detonation wave at Q = 5.00.

Fig. 17.   Arrangement of slanting waves for Ma = 3.0:
a) $\overline{Q}$ = 0; b) $\overline{Q}$ = 1.3

Ignition temperatures were in full conformity with theoretical ignition temperatures. The detonation waves were thin, and total combustion took place already at a distance of about 2 cm from the wave. Combustion taking place in a slanting wave was always strong, and the gas parameters behing the wave - subcritical.

The photos presented in Fig. 16 show cases of shock waves for various values of the other Damkohler number. In these instances the parameters of a straight detonation wave were obtained for the center layer of the stream.

The photo presented in Fig. 17 shows a slanting wave arrangement in case of flow without heat delivery (Q = 0) at Ma = 3. Fig. 17b shows the very same flow, but with heat delivery ($\overline{Q}$ = 1.3). In the photo is clearly visible the rise in shock wave, which is caused by a rise in thermal throttling originated behind the shock wave.

In all instances of detonation, combustion on an obliqued shock wave was only obtained detonation combustion on a strong shock wave (sharp detonation). Flow behind the wave was always subsonic, and the results of the investigations carried out were repeated. Detonation combustion on a weak shock wave could not be obtained.